NATURAL GAS LIQUEFACTION PROCESS

The present invention relates to a method for the liquefaction of a hydrocarbon-rich flow.

Natural gas can be obtained from the earth to form a natural gas feed which must be processed before it can be used commercially. Normally the gas is first pre-treated to remove or reduce the content of impurities such as carbon dioxide, water, hydrogen sulphide, mercury, etc.

The gas is often liquefied before being transported to its point of use to provide liquefied natural gas (LNG). This enables the volume of gas to be reduced by about 600 fold, which greatly reduces the transportation costs. Since natural gas is a mixture of gases, it liquefies over a range of temperatures. At atmospheric pressure, the usual temperature range within which complete liquefaction occurs is -165°C to -155°C. However, since the critical temperature of natural gas is about -80°C to -90°C, the gas cannot be liquefied purely by compressing it. It is therefore necessary to use refrigeration processes.

Natural gas liquefaction plants are either designed as what are known as LNG baseload plants, i.e. plants for the liquefaction of natural gas for the supply of natural gas as primary energy, or as what are known as peak-shaving plants, i.e. plants for the liquefaction of natural gas to cover peak demand.

It is known to cool natural gas by using heat exchangers in which a refrigerant or coolant is used. One well-known method comprises a number of coolant or refrigeration cycles in the form of a cascade.

LNG baseload plants are operated as a rule with coolant circuits consisting of a mixture of

hydrocarbons. These mixed refrigerant circuits are more efficient in terms of energy than expander circuits and make it possible, with the high liquefaction capacities of the baseload plants, for correspondingly relatively low energy consumptions to be achieved.

Conventional liquefaction processes using only two refrigerant cycles are limited to about 5 million tons per annum (mtpa) LNG, unless parallel strings within a single train are considered.

The Mixed Fluid Cascade process is known, e.g. from the US patent 6,253,574, and uses three independent refrigeration cycles, which shifts the limit of a real single train concept with proven compressor drivers to above 8 mtpa LNG.

This method is also known from the German published application 197 16 415.

With liquefaction methods of this type, in principle the first coolant circuit serves to provide pre-cooling, the second coolant circuit serves to provide the liquefaction, and the third coolant circuit serves to provide the sub-cooling for the hydrocarbon-rich flow or natural gas respectively.

Between the pre-cooling and the liquefaction, if necessary, the separation of hydrocarbons with higher boiling points takes place. These are at least those components of the hydrocarbon-rich flow or natural gas which would freeze out during the following cooling stage, i.e. C_5+ hydrocarbons and aromates. Often, in addition, those hydrocarbons, meaning in this situation in particular propane and butane, which would undesirably increase the calorific value of the liquefied natural gas are also separated out before the liquefaction stage.

This separation of hydrocarbons with higher boiling points usually takes place by provision being made for what is known as an HHC (Heavy Hydrocarbon)

column, which serves to separate the heavy hydrocarbons as well as benzene out of the hydrocarbon-rich flow which is to be liquefied. A process stage of this kind is likewise described in the German published application 197 16 415 already mentioned.

Due to the provision of this separation, designated hereinafter as C_3+ separation, at a given pressure of the raw gas the temperature level of the separation of these components is set within comparatively narrow limits.

If the first coolant circuit is now used exclusively for the pre-cooling of the hydrocarbon-rich flow which is to be liquefied before this C_3+ separation, then a part of the overall compression effect of some 40 to 50 % will necessarily be spent on this, while the remaining compression effect of 60 to 50 % will be divided over the second and third coolant circuits.

In the sense of an economical exploitation of the available compressor and drive units, however, the inventors have realised that it is desirable for the (circuit) compressors of the three circuits to retain approximately the same drive capacity, i.e. in each case about a third of the overall drive capacity. This applies in particular to large liquefaction plants with a liquefaction capacity greater than 5 mtpa, because the number of available compressors and drive units for such orders of magnitude is severely restricted. By standardizing the drive units and compressors of the three coolant circuits, it is possible to maximize the attainable liquefaction capacity of the liquefaction process using tried-and-trusted drive units and compressors respectively.

Thus according to one aspect of the invention there is provided an LNG liquefaction process having first and second refrigeration circuits wherein the

second refrigeration circuit is used at least partially for pre-cooling the hydrocarbon-rich stream to be liquefied. Thus the installed power of the gas turbines and starters - at least during normal liquefying operation - can be exploited to the full.

Part of the refrigerant of the liquefaction cycle (LC) may be vaporized under elevated pressure in the precooling section of the process and fed to the LC compressor as a side stream. In this way a substantial load balancing between all the refrigeration cycles can be achieved.

Therefore, according to one aspect of the present invention there is provided a method for the liquefaction of a hydrocarbon-rich flow, in particular of a natural gas flow, whereby the liquefaction of the hydrocarbon-rich flow is effected against a refrigerant circuit cascade consisting of three refrigeration circuits, whereby the first of the three refrigeration circuits serves to provide preliminary cooling, the second refrigeration circuit serves to provide the actual liquefaction, and the third refrigeration circuit serves the sub-cooling of the liquefied hydrocarbon-rich flow, and whereby each refrigeration circuit comprises at least one single-stage or multi-stage compressor, characterised in that at least one part flow of the refrigerant of the second refrigeration circuit is used for the preliminary cooling of the hydrocarbon-rich flow.

From another aspect, the invention provides a method of liquefying a hydrocarbon-rich gas, wherein the gas flows through a cascade of three refrigeration stages, each stage comprising a refrigerant circuit and a compressor, wherein at least part of the flow of refrigerant from the second circuit is used for the preliminary cooling of the hydrocarbon rich gas in the first refrigeration stage.

Preferably the part flow of the refrigerant of the second refrigeration (or cooling) circuit, used for the pre-cooling of the hydrocarbon-rich flow is evaporated at a pressure which is higher than the evaporation pressure of the remaining part flow of the refrigerant of the second cooling circuit, and is conducted to the compressor of the second cooling circuit at an intermediate pressure level.

Preferably the separation of heavier components and/or components of the hydrocarbon-rich flow which freeze out during the liquefaction of the hydrocarbon-rich flow takes place before the actual liquefaction of the hydrocarbon-rich flow.

Preferably the volumes and/or evaporation pressures of the two part flows of the second cooling circuit are changeable.

Preferably at least one part flow of one of the two part flows of the second cooling circuit is used for the provision of cooling in the heavy hydrocarbon separation unit.

The invention therefore provides a load balanced liquefaction process for LNG in which each compressor may have a substantially equal share of the total load, and preferably an equal share. This concept can be applied more widely and hence from another aspect the present invention provides a method of liquefaction comprising a plurality of cooling circuits arranged in a cascade formation, each circuit comprising a compressor, wherein each compressor has a substantially equal share of the total load.

The benefits of load balancing the refrigeration circuits are not limited to any particular type of refrigerant used. However, as mentioned above mixed refrigerant cascades provide an efficient system and therefore in one preferred embodiment the

refrigeration circuits are mixed refrigerant circuits.

Therefore, according to another aspect of the present invention there is provided a method for the liquefaction of a hydrocarbon-rich flow, in particular of a natural gas flow, whereby the liquefaction of the hydrocarbon-rich flow is effected against a mixed refrigerant circuit cascade consisting of three refrigeration circuits, whereby the first of the three refrigeration circuits serves to provide preliminary cooling, the second refrigeration circuit serves to provide the actual liquefaction, and the third refrigeration circuit serves the sub-cooling of the liquefied hydrocarbon-rich flow, and whereby each refrigeration circuit comprises at least one single-stage or multi-stage compressor, characterised in that at least one part flow of the refrigerant of the second refrigeration circuit is used for the preliminary cooling of the hydrocarbon-rich flow.

It will be appreciated that the use of hydrocarbons as refrigerants poses a safety issue and this is particularly significant in the offshore environment, where it is highly undesirable to have large liquid hydrocarbon inventories in what is inevitably a confined space.

Floating LNG production, storage and offloading facilities (LNG FPSOs) are now considered a realistic option for remote offshore gas fields that cannot be economically exploited with conventional onshore technology. A floating concept may soon become the preferred solution for draining deep-water gas reserves.

Therefore the need to increase the safety of such a system is of great importance.

One possibility is to use a nitrogen based process, but this has the significant disadvantage that the thermal efficiency is much lower than a

hydrocarbon based system. In addition, because nitrogen has a low heat transfer coefficient, a large heat transfer area is required to dissipate the waste heat from the process into a cooling medium. Consequently, despite the safety hazards involved, hydrocarbon-based refrigeration cycles continue to be used.

Another non-flammable and inert refrigerant option is carbon dioxide, which may operate in a vapour compression cycle giving reasonable efficiency. Carbon dioxide has a freezing point of -56.6°C, which restricts the minimum possible evaporating temperature due to the risk of dry ice formation. Therefore carbon dioxide is an option for the precooling process only. Since most of the hydrocarbon refrigerant inventory is in the precooling cycle, a change over to CO_2 may still improve the safety of the liquefaction process significantly.

Apart from being non-flammable and its high triple point, carbon dioxide is also distinguished from the common hydrocarbon refrigerants for natural gas precooling by its rather low critical temperature (31.1°C), which is comparable to that of ethane (32.3°C).

WO 01/69149 discloses the possibility of providing a carbon dioxide precooling circuit in a cascade arrangement with a main cooling circuit.

The low critical temperature of CO_2 is a disadvantage since the throttling loss and heat rejection loss in the refrigerating cycle will be larger than for C_3 and C_3/C_2 mixtures. In addition, the heat transfer loss will be larger than with mixed refrigerant due to constant-temperature evaporation.

It has been found that replacing a traditional C_3/C_2 precooling process, for example that disclosed in US 6,253,574, with an equivalent CO_2 process

increases the total power consumption for liquefaction by about 10%, which is considered unacceptable. This consumption increase is due to the reduction in efficiency of the cycle due to the low critical temperature of carbon dioxide. In addition, the evaporating temperature in the first stage of the CO_2 precooling cycle is only a few degrees higher than the CO_2 triple point. This leads to operational problems and a danger of dry ice formation.

There therefore exists a need for an efficient liquefaction process containing a CO_2 precooling circuit.

The applicants of the present invention have realised that a carbon dioxide pre-cooling circuit can be combined with the load balanced liquefaction process described above in order to overcome the above discussed problems with using carbon dioxide.

Therefore, in a preferred embodiment of the present invention the first refrigeration circuit comprises carbon dioxide.

This concept is considered inventive in its own right and therefore, according to another aspect of the present invention there is provided a substantially load balanced mixed refrigerant cascade process comprising a carbon dioxide pre-cooling circuit.

As the liquefaction compressor takes over some of the pre-cooling cycle load, the carbon dioxide circuit can be operated to provide a higher minimum evaporation temperature and thus the risk of dry ice formation is reduced. In addition, as the load of the carbon dioxide cycle is reduced the impact of the lower thermodynamic efficiency of CO_2 compared with C_2/C_3 is alleviated. In a load balanced process where each compressor contributes a third of the total power consumption, the increase in power consumption

caused by using CO_2 can be reduced to only a few percent greater than when using hydrocarbons.

In order to achieve maximum efficiency from the carbon dioxide circuit it is preferable that the carbon dioxide is cooled after condensation to a temperature of 20°C or less, more preferably to 15°C or less. This can be achieved using air cooling although preferably cold cooling water is used. As the invention is particularly suited for offshore application the water is preferably sea water, preferably extracted from a depth suitable to give the required low temperature.

Preferably therefore the carbon dioxide pre-cooling cycle includes a sub-cooling heat exchanger installed after the condenser.

Using this method the reduction in total power consumption is great enough to make using a CO_2 pre-cooling circuit a viable option in both on and offshore LNG facilities.

Preferably the carbon dioxide cooling circuit comprises three pressure levels in order to improve the thermodynamic efficiency of the process.

In order to reduce the internal heat load of the precooling circuit it is preferable that only a substream of carbon dioxide is subcooled in the pre-cooling circuit. This is unlike the second and third cooling cycle refrigerants, the full sub-cooling of which increases the efficiency of the process.

The higher operating pressure required when using CO_2 means that it my be preferable to use a high pressure casing with the carbon dioxide compressor. More preferably the compressor can be split into two casings and a barrel type casing used for the high pressure stage.

According to another aspect of the present invention there is provided a LNG liquefaction process comprising three cascade cycles each driven

by a compressor, wherein the compressors are substantially equally loaded and one of the cascade cycles is a carbon dioxide cycle.

According to a further aspect of the present invention there is provided a carbon dioxide pre-cooling circuit for LNG liquefaction wherein the carbon dioxide has a minimum evaporation temperature of no less then -50°C, preferably no less than -40°C and most preferably no less than -35°C.

Preferred embodiments of the present invention shall now be described, by way of example only, with reference to the following drawings, in which:

FIG 1 shows a load balanced liquefaction process in accordance with a preferred embodiment of the invention;

FIG 2 show an alternative embodiment of a load balanced process;

FIG 3 shows a graph of overall power demand as a function of a reference temperature;

FIG 4 shows a load balanced liquefaction process containing a carbon dioxide pre-cooling circuit;

FIG 5 shows hot/cold composite curves for the processes shown in FIGs 2 and 4; and

FIG 6 shows a comparison of refrigerant inventories of the processes shown in FIGs 2 and 4.

In FIG 1 the cooling and liquefaction of the hydrocarbon-rich flow, which is conducted via line 1, are effected against a mixed refrigerant circuit cascade, consisting of three mixed refrigerant circuits. These as a rule have different compositions, such as are described, for example, in the aforementioned German published application 197 16 415.

The hydrocarbon-rich flow which is to be liquefied is cooled in the heat exchanger E1 against the two evaporating mixed refrigerant flows 4b and 4d

of the first mixture circuit 4a to 4e, then cooled by the evaporating mixed refrigerant flow 3d, and then conducted via line 1a to a heavy hydrocarbon separation unit S, represented simply as a box.

In this separation unit S the C_{3+} separation described heretofore takes place, whereby the components separated out of the hydrocarbon-rich flow are drawn off from the heavy hydrocarbon separation unit S via line 1b.

According to one advantageous embodiment of the method according to the invention, not shown in the drawing, at least one part flow of one of the two part flows 3b and 3d of the second cooling agent mixture circuit 3a to 3e, which will be discussed in greater detail hereinafter, is used for the provision of cooling in the separation unit S. In this situation, the choice of which of the two part flows 3b and/or 3d is drawn from for this provision of cooling is determined by the temperature level(s) required in the heavy hydrocarbon separation unit S.

The hydrocarbon-rich flow to be liquefied is then conducted via line 1c to a second heat exchanger E2, and is liquefied in this against the evaporating mixed refrigerant flow 3b of the second cooling circuit 3a to 3e.

Once liquefaction has taken place, the hydrocarbon-rich flow is conducted via line 1d to a third heat exchanger E3, and is subcooled here against the mixed refrigerant flow 2b of the third cooling circuit 2a to 2c. The subcooled liquid product is then conducted via line 1e to its further use.

As can be seen from the drawing, each of the three cooling circuits 2a to 2c, 3a to 3e, and 4a to 4e, has a compressor, V2, V3, and V4 respectively. Not shown in the drawing are the corresponding drives for these compressors V2, V3, and V4. In addition, the coolers or heat exchangers which are located

downstream of the compressors V2, V3, and V4 respectively are not shown in the drawing, in which the refrigerant mixture is cooled against a cooling medium, such as water.

The refrigerant mixture of the first refrigerant circuit, compressed in the compressor V4, is conducted via line 4a to the heat exchanger E1, and is divided here into two part flows 4b and 4d after cooling has taken place. The refrigerant mixture in these part flows 4b and 4d, after throttling has been effected in the valves d and e or expansion devices, is evaporated to different pressure levels in the heat exchanger E1 and then conducted via line 4c or 4e to the compressor V4 before the first stage (part flow 4c) or to an intermediate pressure level (part flow 4e).

The refrigerant mixture of the second cooling circuit 3a to 3e, compressed in the compressor V3, is conducted via line 3a through heat exchangers E1 and E2, and is cooled in these. That part flow 3b of this refrigerant mixture flow, which is conducted through heat exchanger E2, after expansion in valve b, is evaporated in heat exchanger E2 against cooling process flows, and is then conducted via line 3c to the intake stage of compressor V3.

According to the invention, a part flow 3d of the refrigerant mixture of the second refrigerant mixture circuit 3a to 3e is drawn off after the heat exchanger E1, expanded in valve c, and then evaporated in heat exchanger E1 against cooling process flows, before being conducted via line 3e, at an intermediate pressure level, to the circuit compressor V3. Accordingly, the refrigerant mixture part flow 3d, according to the invention, makes a contribution to the pre-cooling of the hydrocarbon-rich flow in heat exchanger E1.

In order for this to be achieved, the part flow 3d of the refrigerant mixture of the second mixed

refrigerant circuit 3a to 3e, used for the pre-cooling of the hydrocarbon-rich flow, must be evaporated at a pressure which is higher than the evaporation pressure of the mixed refrigerant part flow 3b of the second mixed refrigerant circuit 3a to 3e.

By selecting the intermediate pressure at which the mixed refrigerant part flow 3e is evaporated and conducted to the compressor V3, and by regulating the volume distribution of the two mixed refrigerant part flows 3b and 3d, the distribution of the cooling capacity of the second refrigerant circuit onto the heat exchangers E1 and E2, and therefore to the pre-cooling and liquefaction of the hydrocarbon-rich flow which is to be liquefied, can be adjusted almost at will.

If, for example, 40 % of the total drive capacity is required for the pre-cooling and 60 % for the liquefaction and subcooling of the hydrocarbon-rich flow, then, with the concept and method according to the invention, one compressor is used in each case with a third of the total drive capacity in the first and third refrigerant mixture circuit, i.e. for the pre-cooling as well as for the subcooling of the hydrocarbon-rich flow which is to be liquefied. The compressor of the second refrigerant mixture circuit is operated according to the invention in such a way that it uses 20 % of its capacity, and consequently 6.66 % of the total capacity, for pre-cooling, while the remaining 80 %, i.e. 26.66 % of the total capacity, is used for liquefaction.

The method according to the invention accordingly makes possible the economical exploitation of the available compressors and drive units, because the (circuit) compressors of the three refrigerant circuits obtain approximately the same drive capacity, i.e. a third of total capacity in each case. Accordingly, large liquefaction plants in particular,

with a liquefaction capacity greater than 5 million tonnes LNG per year, can be operated substantially more economically, since, by standardizing the drives and compressors of the three cooling circuits, the achievable liquefaction capacity of the liquefaction process can be maximised with the use of tried-and-trusted drive units and compressors.

FIG 2 shows an alternative version of the load balanced process. As with FIG 1 the pre-cooling cycle C10 comprises a first circuit driven by a first compressor V10 and one part 22 of the refrigerant stream 21 from the second cycle C20. Three General Electric MS 7121 EA (Frame 7) gas turbines are used to drive the compressors V10, V20, V30. If highest availability is of the essence, the three refrigeration cycles can be designed with two times 50% gas turbine/compressor trains. In this case six GE MS 6581 B (Frame 6) gas turbines would replace the three Frame 7s.

All LNG plants require the extraction of at least of those hydrocarbons, which would freeze in the LNG under storage conditions (e.g. aromatics and C_5+). In an LNG plant precooling is usually considered as first cooling step between ambient temperature and extraction of the mentioned hydrocarbons.

It should be emphasised that the method according to the invention can be combined with all known separation methods considered to be prior art for relatively high-boiling hydrocarbons.

The precooling portion of the overall power demand of all refrigeration compressors for the two gases defined in Table 1 is shown in FIG 3 as a function of a reference temperature. This is the temperature, under which all main process streams (natural gas, refrigerant fluids) enter into the cryogenic heat exchangers.

Table 1

mol%	**Lean Gas**	Rich Gas
N_2	**5.00**	5.00
CH_4	**88.93**	84.07
C_2H_6	**3.96**	5.58
C_3H_8	**1.37**	2.73
C_4H_{10}	**0.48**	1.34
C_5H_{12}	**0.17**	0.65
C_6H_{14}	**0.06**	0.32
C_7H_{16}	**0.02**	0.16
C_8H_{18}	**0.01**	0.08
Benzene	**0.01**	0.08
	100.00	100.00

The lower the reference temperature and the richer the gas the smaller the required compressor power for precooling becomes. This situation can be addressed reasonably well by designers of dual flow liquefaction processes, if the power mismatch between precooling and liquefaction plus subcooling is compensated by helpers for the gas turbines.

A process with three refrigeration cycles offers a much wider field for even load distribution between the cycles. If part of the refrigerant of the liquefaction cycle C20 is vaporized under elevated pressure in the precooling section C10 and is fed to the LC compressor V20 as side stream 22, a perfect load balancing between all three refrigeration cycles can be achieved. This feature is a major aspect of a cost effective design for large production capacities. As all three (3) cycles are symmetrically driven this arrangement is referred to as MFC®s3.

Unlike the embodiment of FIG 1, the final compressor V30 of FIG 2 is split into two casings V31, V32. The second casing V32 is designed to deal

with high pressures at which the multistage compressor operates.

In order to provide actual figures for a realistic process design a large LNG train has been studied. On the basis of the lean gas composition with a pressure of 62 bar and a temperature of 35 deg C at the inlet to precooling a conceptual process design was made. The refrigeration compressors are driven by Frame 7's with additional 20 MW on each shaft, which have been recruited from the starter/helpers. The resulting LNG rundown amounts to 8.5 mtpa at 333 stream days, which is accompanied by an additional quantity of 0.4 mtpa NGL (C_3+ hydrocarbons). The specific energy consumption of the refrigeration compressors is 259 kWh/t_{LNG}.

In FIG 4 the precooling circuit C10 of FIG 2 has been replaced with a pre-cooling circuit C100 which comprises a carbon dioxide stream 101. After compression and condensation/subcooling the stream 101 is split into three separate streams, 102, 103, 104 which are then expanded to different pressures. This compensates for the constant temperature evaporation of CO_2. Unlike hydrocarbon streams 201, 301 only part of the carbon dioxide stream 101 is sub-cooled by the pre-cooling heat exchanger E100 prior to expansion, in order to reduce the internal heat load of this exchanger.

Owing to the higher operating pressure, the CO_2 precooling compressor V100 is split into two casings, V110, V120 with a barrel type casing V120 for the high-pressure stage. After compression the carbon dioxide is cooled by a water cooled condenser C20 and an additional subcooling heat exchanger C22, using seawater to subcool the liquid refrigerant after the condenser C20, in order to improve process efficiency. In addition a desuperheater can also be

provided after the compressor, as in many conventional systems.

As with the previous embodiments, "load balancing" is achieved by allowing the liquefaction compressor V200 to take over some of the precooling cycle load, leading to a "symmetrical" process.

Process simulations of the above embodiment as shown in FIG 4 and FIG 2 gave power requirement data as shown in Table 2, using the design data as shown in Table 3. As a result of the load-balanced process, the power input to the CO_2-precooled case was only 4.4% higher than the baseline. For a given maximum available power as defined by the hydrocarbon process case, this would correspond to a LNG capacity of 95.6% with CO_2 precooling unless more driver capacity is installed.

Table 2

	CO_2 precooling	C_2/C_3 precooling	
Total shaft power	162.7 (104%)	155.8 (100%)	MW
Precooling compressor	49.6	47.6	MW
Liquefaction compressor	50.5	47.7	MW
Subcooling compressor	50.5	48.5	MW
Other power consumers	12.1	12.0	MW

Table 3

LNG production capacity	5.8	mtpa
Gross calorific value of LNG	40	MJ/Sm^3
Feed gas pressure (liquefaction inlet)	69	bar
Sea cooling water temperature	5	°C

Temperature profiles in the form of hot/cold composite curves for the two cases are shown in Figure 5. The three CO_2 precooling temperature levels are easily observed in the left diagram. The highest pressure level to the liquefaction compressor is also considered part of precooling. Changes in the subcooling process are minimal between the two cases.

Layout, size and weight of an offshore LNG liquefaction module with CO_2 precooling were compared to the baseline hydrocarbon case (that shown in FIGs 1 and 2). Among the factors that contributed to reduce the equipment footprints and give smaller dimensions with CO_2 were reduced precooling compressor suction drum sizes and smaller precooling piping dimensions. Additional equipment caused by the third precooling pressure level/drum and the installation of a refrigerant subcooler made the net reduction in footprint area marginal, however. The plate-fin heat exchangers were reduced in size due to larger LMTD (Logarithmic Mean Temperature Difference) and less internal duty. While plate fin heat exchangers were used in this instance it is of course also possible to use other types of heat exchangers, which could also be reduced in size. Some of the major pipe sizes in the liquefaction and subcooling circuit did not change much, and it is these pipes that to a large degree set out the deck heights, so no changes were envisaged relative to deck elevations. In total, it was concluded that the liquefaction module size would be no greater when using a CO_2 precooling circuit, and indeed a reduction of a few square meters is possible. In addition, the weight of the module dropped by 100 tons.

A major safety concern of the LNG process with hydrocarbon precooling, especially when applied offshore, is the possible formation of a flammable and explosive hydrocarbon/air mixture in case of a

major leakage in one of the refrigerant circuits. Thus, the minimization of hydrocarbon refrigerant inventory is very important in terms of safety.

As may be observed from the FIG 6, the HC refrigerant inventory is reduced by about 70% in the CO_2-precooled process. The reduced hydrocarbon charge is positive in relation to loss prevention and to the availability of the three main safety functions of the LNG barge, which are (i) main structural strength, (ii) main escape routes, and (iii) means of evacuation.

If the molecular weight of the hydrocarbon refrigerant is higher than that of air, a flammable cloud can accumulate inside or between the modules, and on the deck surfaces. Thus, in addition to minimizing the total hydrocarbon inventory it is of special importance to eliminate the heavier components, especially propane (52% heavier than air), but also ethane (4% heavier than air). By replacing the hydrocarbon precooling with CO_2, all propane is eliminated from the liquefaction module, and even though ethane is present in the liquefaction and subcooling refrigerants, both these mixtures have a molar mass that is lower than air.

From the above results it has been found that the introduction of CO_2 precooling in a load-balanced MFC®s3 process does not give a significant increase in specific power requirement, or equipment size/weight/cost, while the safety of the process can be improved.